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Introduction

Gas bubbles are ubiquitous in organic-rich, muddy sediments of coastal waters and shallow adjacent seas (Judd and Hovland, 1992; Richardson and Davis, 1998). Depths and horizontal distributions of these gas-charged sediments are usually determined from seismic profiling. The presence of gas bubbles often impedes acoustic characterization of sediments below the gas horizon and terms such as acoustic masking or blanking, acoustic turbidity, bright spots, wipeouts, and pulldowns are used to characterize these gas-charged sediments. Acoustic turbidity also produces anomalously high acoustic backscattering from the seafloor (Lyons et al., 1996: Tang, 1996) degrading the effectiveness of high-frequency sonar. Models of acoustic-bubble interactions in fine-grained sediments developed by Anderson and Hampton (1980) have been corroborated by laboratory (Gardner, 2000) and field (Wilkens and Richardson, 1998; Lyons et al., 1996: Tang, 1996, Anderson et al., 1998) experiments. In this paper, we model the effects of bubble volume, bubble size and bubble distribution on sound speed and attenuation in the well-characterized sediments of Eckernförde Bay, Baltic Sea and from experiments recently conducted in Cape Lookout Bight, North Carolina. These two areas constitute the best known and most studied area of gassy sediment in the world (Richardson and Davis, 1998; Martens et al., 1998) thus providing the ideal settings for such comparisons.

15. SUBJECT TERMS
Acoustic Propagation gas bubbles, acoustic masking, blanking, turbidity, Eckernforde Bay, Cape Lookout Bight, North Carolina

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ACOUSTIC PROPAGATION IN GASSY SEDIMENTS

M.D. Richardson and W.T. Wood

Marine Geosciences Division, Naval Research Laboratory
Stennis Space Center, Mississippi 39529-5004, USA
Mike.Richardson@nrlssc.navy.mil

Introduction

Gas bubbles are ubiquitous in organic-rich, muddy sediments of coastal waters and shallow adjacent seas (Judd and Hovland, 1992; Richardson and Davis, 1998). Depths and horizontal distributions of these gas-charged sediments are usually determined from seismic profiling. The presence of gas bubbles often impedes acoustic characterization of sediments below the gas horizon and terms such as acoustic masking or blanking, acoustic turbidity, bright spots, wipeouts, and pulldowns are used to characterize these gas-charged sediments. Acoustic turbidity also produces anomalously high acoustic backscattering from the seafloor (Lyons et al., 1996; Tang, 1996) degrading the effectiveness of high-frequency sonar. Models of acoustic-bubble interactions in fine-grained sediments developed by Anderson and Hampton (1980) have been corroborated by laboratory (Gardner, 2000) and field (Wilkens and Richardson, 1998; Lyons et al., 1996; Tang, 1996, Anderson et al., 1998) experiments. In this paper, we model the effects of bubble volume, bubble size and bubble distribution on sound speed and attenuation in the well-characterized sediments of Eckernförde Bay, Baltic Sea and from experiments recently conducted in Cape Lookout Bight, North Carolina. These two areas constitute the best known and most studied area of gassy sediment in the world (Richardson and Davis, 1998; Martens et al., 1998) thus providing the ideal settings for such comparisons.

Study sites: ***Cape Lookout Bight, North Carolina:*** This shallow (4-7 m water depth) coastal basin acts as a trap for organic matter exiting a back barrier island lagoon system and has the highest rates of anaerobic mineralization measured in coastal sediments (Martens and Van Klump, 1984). Methane production is highest during warm summer months with methane saturation and bubbles occurring within 10 cm bsf (below seafloor) and gas volumes as high as 12% (Martens et al., 1998). During the summer, ebullition of methane gas occurs at low tide through open cavities called "mud tubes" and methane fluxes, via ebullition, nearly equal sediment methane production rates. In the winter, methane production rates drop and

much less methane escapes the sediment. Near surface sediment gas volume is lower and methane saturation and bubbles occurs below 30 cm bsf.

Eckernförde Bay, Baltic Sea: Eckernförde Bay is the best-known and most studied gassy sediment in the world (Richardson and Davis, 1998). As early as the studies of Schüler (1952), acoustic turbidity at this site was attributed to the presence of free gas in the sediments. The uppermost acoustic horizon ranges from 50 to 200 cm bsf and migrates vertically in response to temperature, nearer the sediment-water interface when sediments are warmest (Wever and Fiedler, 1995). Rates of anaerobic mineralization are lower than at the Cape Lookout Bight site and methane concentrations vary little with season (Martens et al., 1998; Anderson et al., 1998). The bubbles resolvable by CT scan imagery range from 0.5 to 5 mm in equivalent radius with 0 - 2 % (mean 0.1 %) percent methane by volume. Higher gas volumes (up to 6%) have been reported from the numerous pockmarks. Considerable horizontal variability was found in methane bubble concentrations (by volume, number of bubbles, and size distribution) in cores collected 2-20 meters apart (Anderson et al., 1998).

Acoustic Model Predictions

Modified versions (Lyons et al., 1996; Anderson et al., 1998; Richardson and Wilkens, 1998) of the acoustic propagation models first developed by Anderson and Hampton (1980) were used to predict frequency dependent sound speed and attenuation in gassy sediments of Cape Lookout Bight and Eckernförde Bay. These models assume bubbles are large relative to particle size and that the structure of the sediment frame interacts with the bubbles and changes bubble resonance, compressibility, absorption, and scattering. The low sediment permeability, in the modeled sediments, restricts pore fluid motion and allows the use of the visco-elastic propagation models used in this paper to approximate sediment propagation predicted by more complex poro-elastic models (Stoll, 1998). Bubble size distributions in Eckernförde Bay sediments were measured using CT-scans (Anderson et al., 1998); whereas, bubble volumes for the sediments from Cape Lookout were estimated using x-radiography (Martens and Van Klump, 1980). Values of sediment and gas physical properties given by Wilkens and Richardson (1998) were used to predict sound speed and attenuation in both the gassy sediments of Eckernförde Bay and Cape Lookout Bight.

Sound speed and attenuation were first calculated assuming the entire volume of gas (0.1 to 12%) consisted of a single bubble size (Fig. 1). Most authors have used this approach because the actual distribution volumes within bubbles sizes are rarely available. Below bubble resonance (lower left quadrant of the panels in Figure 1) the sound speed ratio (ratio of sediment sound speed to sound speed of the pore water) decreases and attenuation increases with gas volume.

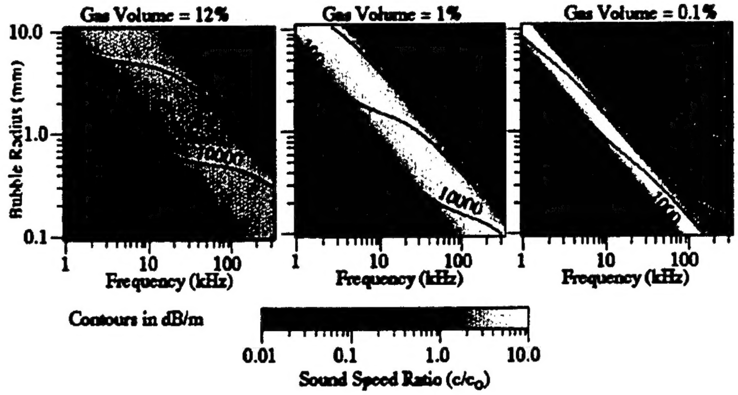

Fig. 1: Sound speed ratio (sediment sound speed divided/ pore water sound speed) and attenuation (dB m^{-1}) as a function of bubble size and acoustic frequency for bubble concentrations (12%, 1% and 0.1%) typical of Eckernförde Bay and Cape Lookout Bight.

Near bubble resonance attenuation is very high, especially at high gas volumes. Well above bubble resonance (upper right quadrants of panels in Fig. 1), sound speed is near bubble free sediments (sound speed ratio = 1) at gas volumes typical of Eckernförde Bay but much higher than gas free sediments at gas volumes typical of Cape Lookout Bight.

Sound speed and attenuation were then predicted as a function of bubble size and acoustic frequency for typical bubble concentrations found in Eckernförde Bay sediments (Fig. 2). At acoustic frequencies well above resonance (>30 kHz), bubble resonance rarely affects sound speed. Intrinsic attenuation is low and scattering from bubbles (not included in the model) probably dominates attenuation. At frequencies well below resonance (< 1 kHz) "compressibility effects" dominate, sound speed is much lower (250 m s^{-1}), and attenuation is low. Near resonance sound speed varies greatly with frequency and attenuation is very high. Analysis of in situ and remote acoustic propagation and scattering data over a frequency range of 5-400 kHz, support these model predictions (Wilkens and Richardson, 1998), especially at acoustic frequencies well above and well below the bubble resonance. Analysis of the dispersion of measured sound speeds established the upper limit of methane bubble resonance at 20-25 kHz. These data, combined with bubble sizes determined from CT scan imagery yielded estimates of effective bubble sizes between 0.3 and 8.0 mm. The lower limit of effective bubble size was smaller than the resolution of the CT-scanning technique. Values of sound speed predicted using the entire spectrum of bubble sizes (Fig. 2) were lower than predicted values based on a single bubble size (Fig. 1). These predictions are in concordance with sound speeds (1100 –1200 m s^{-1}) reported for 5-15 kHz by Wilkens and Richardson (1998) and suggest that the proportional distribution of bubbles must be considered when predicting acoustic behavior of gassy sediment.

The bubble size spectrum provided by Martens and van Klump (1980) was used to predict sound speed and attenuation in sediments of Cape Lookout Bight (Fig 3). Note that the number of bubbles and average radii are much greater than reported for sediments in Eckernförde Bay (Fig. 2). In situ measurements of sound speed and attenuation in the upper 2-m of sediments at Cape Lookout Bight were made using wide-bandwidth transducers (5-200 kHz). These cross-hole measurements were made during winter conditions (May) and will be repeated during summer (June-October) conditions. Comparisons of recent measurements (May, 2000) and predictions presented in Fig. 3 will be presented.

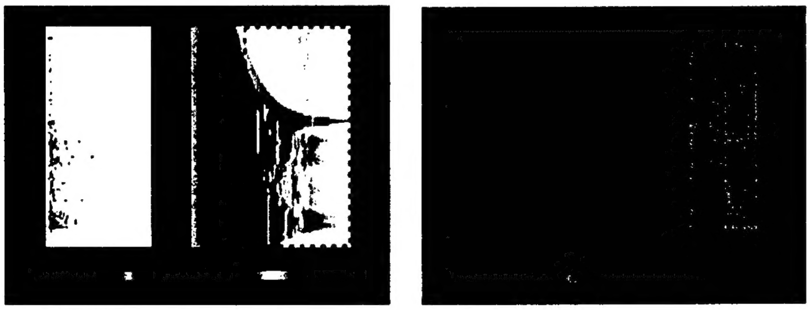

Fig. 2: Sound speed ratio and attenuation calculated for a measured bubble size distribution (site P2) typical of sediments of Eckernförde Bay (see Anderson et al., 1998) and the sediment properties given by Wilkens and Richardson (1998).

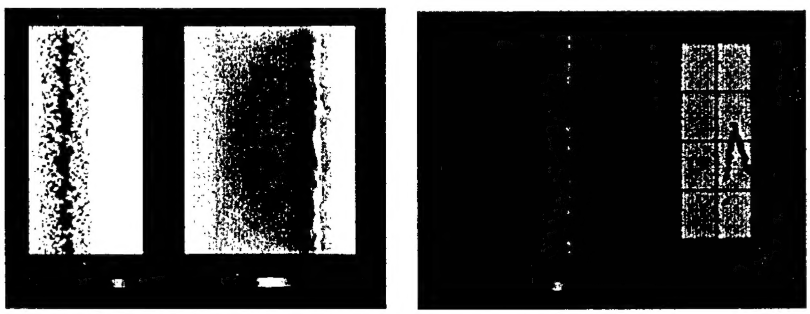

Fig. 3: Sound speed ratio and attenuation calculated for a measured bubble size distribution typical of sediments of Cape Lookout Bight (see Martens and Van Klump, 1980, 1984) and the sediment properties given by Wilkens and Richardson (1998).

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